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THE OPTICAL COUNTERPART OF THE ACCRETING MILLISECOND PULSAR SAX J1808.4–3658 IN OUTBURST: CONSTRAINTS ON THE BINARY INCLINATION

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ABSTRACT

We present multiband optical/infrared photometry of V4580 Sgr, the optical counterpart of the accretion-powered millisecond pulsar SAX J1808.4–3658, taken during the 1998 X-ray outburst of the system. The optical flux is consistent with emission from an X-ray–heated accretion disk. Self-consistent modeling of the X-ray and optical emission during the outburst yields best-fit extinction $A_V = 0.68^{+0.37}_{-0.15}$ and inclination $\cos i = 0.65^{+0.23}_{-0.33}$ (90% confidence), assuming a distance of 2.5 kpc. This inclination range requires that the pulsar's stellar companion has extremely low mass, $M_c = 0.05$–$0.10 \, M_\odot$. Some of the infrared observations are not consistent with disk emission and are too bright to be from either the disk or the companion, even in the presence of X-ray heating.

Subject headings: accretion, accretion disks — binaries: close — pulsars: individual: SAX J1808.4–3658 — stars: individual: V4580 Sgr — stars: neutron

1. INTRODUCTION

It is generally believed that millisecond radio pulsars are formed during sustained mass transfer onto neutron stars in X-ray binaries (e.g., Bhattacharya & van den Heuvel 1991). Only one example of a presumed progenitor, an accretion-powered millisecond X-ray pulsar, is currently known. The X-ray transient SAX J1808.4–3658 ($l = 355.4°$, $b = −8.1°$) was discovered in 1996 September by the *BeppoSAX* Wide Field Cameras during a ∼20 day transient outburst (in't Zand et al. 1998). Based on the detection of Eddington-limited thermonuclear X-ray bursts during these observations, the source distance is estimated to be 2.5 kpc (in 't Zand et al. 2001). A second source outburst was detected with the *Rossi X-ray Timing Explorer (RXTE)* in 1998 April (Marshall 1998). Timing analysis of the 2–30 keV *RXTE* data revealed the presence of a 401 Hz pulsar in a 2-hr binary with a low-mass companion (Wijnands & van der Klis 1998; Chakrabarty & Morgan 1998).

Shortly after the initial *RXTE* detection of the 1998 X-ray outburst, we observed a $V ≈ 16$ star located 19 arcsec from the center of the *BeppoSAX* error circle; this star was not present on the Digitized Sky Survey image of the field to a limiting magnitude of $V \gtrsim 19$, leading to its identification as the optical counterpart of SAX J1808.4–3658 (Roche et al. 1998). The optical intensity of this source faded as the X-ray source declined, and a 2-hr orbital modulation was marginally detected in the optical flux (Giles, Hill, & Greenhill 1999). This 2-hr optical modulation was subsequently confirmed in observations during quiescence (Homer et al. 2001). The optical counterpart has been designated V4580 Sagittarii (Kazarovets, Samus, & Durlevich 2000). In this *Letter*, we report on optical/IR photometry obtained during the 1998 outburst.

2. OBSERVATIONS AND RESULTS

We obtained multiband optical photometry of the SAX J1808.4–3658 field at several epochs during the 1998 X-ray outburst using the $f/15$ Cassegrain CCD imager on the 1-m Jacobus Kapteyn Telescope (JKT) at the Observatorio del Roque de los Muchachos, La Palma, Canary Islands, Spain. Additional optical observations were obtained at various epochs during the outburst using the Keck 10-m telescope in Mauna Kea, Hawaii; the 3.5-m New Technology Telescope (NTT) at the European Southern Observatory (ESO) in La Silla, Chile; and the 1.9-m telescope at the South African Astronomical Observatory. Infrared photometry was also obtained at several epochs using the 3.8-m United Kingdom Infrared Telescope (UKIRT). A summary of these observations is given in Table 1. For completeness, we have also included the photometry obtained by other groups as well (Giles et al. 1999; Percival et al. 1998; Homer et al. 2001).

The V-band flux history is shown in Figure 1, along with the X-ray flux history measured by the *RXTE* Proportional Counter Array (PCA; Gilfanov et al. 1998). On both plots, we have also indicated the quiescent flux levels measured well after outburst (Wijnands et al. al. 2001; Homer et al. 2001). It is interesting to compare the behavior of the X-ray and optical light curves. In the X-ray band, the intensity shows a steady exponential decay ($τ = 10.9$ d) until about MJD 50929, when there is a sharp break to a steeper decay ($τ = 2.2$ d), as shown previously by Gilfanov et al. (1998). The optical V-band light curve also shows an initially exponential decay in intensity ($τ = 8.4$ d) until MJD 50936, when it abruptly reaches a plateau lasting at least 30 d. Despite the fact that the optical light curve appears to roughly follow the X-ray light curve early in the outburst, the breaks

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Table 1
Optical/IR Photometry of SAX J1808.4–3658[a]

| UT Date | MJD | Telescope | Magnitudes | | | | | | | Ref. |
			B	V	R	I	J	H	K	
1998 Apr 16.6	50919.6	Keck 10-m	...	...	16.19(3)	...	...	...	...	1
1998 Apr 18.2	50921.2	JKT 1-m	...	16.51(9)	16.19(15)	15.89(13)	...	...	...	1
1998 Apr 18.6	50921.6	UKIRT 3.8-m	...	...	...	...	15.06(2)	14.34(1)	13.76(3)	1
1998 Apr 18.7	50921.7	Mt. Canopus 1-m	...	16.72	...	16.11(5)	...	...	...	2
1998 Apr 22.7	50925.7	Mt. Canopus 1-m	...	16.77	...	...	...	...	...	2
1998 Apr 24.2	50927.2	JKT 1-m	17.43(10)	17.12(7)	16.82(6)	16.50(8)	...	...	...	1
1998 Apr 27.7	50930.7	Mt. Canopus 1-m	...	17.81	...	17.36(13)	...	...	...	2
1998 Apr 28.0	50931.0	SAAO 1.9-m	...	17.74(8)	...	17.13(11)	...	...	...	1
1998 Apr 29.7	50932.7	Mt. Canopus 1-m	...	18.17(6)	...	17.67(6)	...	...	...	2
1998 May 02.6	50935.6	UKIRT 3.8-m	...	...	...	...	...	...	17.17(4)	3
1998 May 02.7	50935.7	Mt. Canopus 1-m	...	18.58(11)	...	17.83(10)	...	...	...	2
1998 May 04.6	50937.6	UKIRT 3.8-m	...	...	...	...	...	...	17.33(4)	3
1998 May 04.7	50937.7	Mt. Canopus 1-m	...	18.36(7)	...	17.83(13)	...	...	...	2
1998 May 05.1	50938.1	JKT 1-m	18.67(18)	18.51(15)	18.06(14)	17.92(25)	...	...	...	1
1998 May 05.7	50938.7	Mt. Canopus 1-m	...	18.50(9)	...	18.12(15)	...	...	...	2
1998 May 16.7	50949.7	Mt. Canopus 1-m	...	18.36(14)	...	17.80(15)	...	...	...	2
1998 May 17.5	50950.5	Mt. Canopus 1-m	...	18.44(5)	...	17.84(6)	...	...	...	2
1998 Jun 02.4	50966.4	NTT 3.5-m	...	18.59(5)	...	...	...	...	...	1
1998 Jun 27.7	50991.7	Mt. Canopus 1-m	...	> 20.5	...	...	...	...	...	1
1998 Sep 07.6	51063.6	UKIRT 3.8-m	...	...	...	...	>19.3	...	>18.3	1
2000 Jul 03	51728	SAAO 1.9-m	22.0(1)	21.5(1)	20.9(1)	...	...	...	...	4

[a]Where multiple measurements were obtained on the same day from a given observatory, we present the average value. Measurement uncertainties are quoted at the 1σ level.

References. — (1) This work; (2) Giles et al. 1999; (3) Percival et al. 1998; (4) Homer et al. 2001.

from the initial decay are spaced by a week, and the behavior after the break is quite different in the two bands.

The broadband optical/IR spectrum is shown in Figure 2 for several epochs during the outburst, as well as a quiescent measurement. The shape of the $BVRI$ spectrum during the outburst remains roughly constant, and we show below that this shape is easily consistent with an X-ray heated disk model. There is an obvious infrared excess on MJD 50921, with the JHK points lying well above an extrapolation of the $BVRI$ spectrum. By contrast, the K point for MJD 50938 is consistent with the extrapolated optical spectrum. Since the origin of the IR excess early in the outburst is unclear, we restrict our accretion disk fitting in the next section to the optical $BVRI$ bands, which (along with the ultraviolet and soft X-ray) is where most of the disk emission from an LMXB accretion disk is expected.

One point of concern is the discrepancy between optical intensities measured at different observatories a short time apart. This is particularly evident in the JKT and Mt. Canopus observations on MJD 50921, which were spaced by half a day but differ by 0.2 magnitudes in V and I. One possible contribution to this discrepancy is the 2-hr orbital flux modulation reported by Giles et al. (1999), with amplitude of $\simeq 0.07$ magnitudes. To account for this in our fits, we added a systematic uncertainty of this size in quadrature to the statistical uncertainties quoted in Table 1. However, even this systematic uncertainty is insufficient to explain the discrepancy, which we conclude largely arises from further systematic errors due to calibration uncertainties in the JKT data. In particular, several of the JKT service observations suffered from limited or insufficient calibration measurements. We therefore adopt a systematic uncertainty of 0.2 magnitudes for all the JKT measurements in our model fitting.

3. SPECTRAL FITTING

The optical data during outburst are well fitted by an X-ray–heated accretion disk model (see Vrtilek et al. 1990, Chakrabarty 1998, and references therein). We summarize this model here. The observed flux from the accretion disk at frequency ν can be written as

$$F_\nu = \frac{4\pi h \nu^3 e^{-A_\nu/1.086} \cos i}{c^2 D^2} \int_{r_{\rm in}}^{r_{\rm out}} \frac{r\,dr}{\exp[h\nu/kT(r)]-1}, \quad (1)$$

where D is the source distance, A_ν is the (frequency-dependent) interstellar extinction in magnitudes, r is the mid-plane disk radius coordinate, $r_{\rm in}$ and $r_{\rm out}$ are the inner and outer radii of the disk, and the disk's surface temperature profile $T(r)$ is given by

$$T^4(r) = \frac{3GM_{\rm x}\dot{M}}{8\pi\sigma r^3} + \frac{L_{\rm x}(1-\eta_{\rm d})}{4\pi\sigma r^2}\left(\frac{dH}{dr} - \frac{H}{r}\right). \quad (2)$$

Here, $M_{\rm x}$ is the neutron star mass, $\dot{M}$ is the mass transfer rate through the disk, $L_{\rm x}$ is the X-ray luminosity of the neutron star, $\eta_{\rm d}$ is the X-ray albedo of the disk, and H is the disk's scale height. $H(r)$ may be determined from the condition of hydrostatic equilibrium, as in a standard Shakura-Sunyaev disk model (see, e.g., Frank, King, & Raine 1992). The first term in equation (2) is due to internal viscous heating in the disk, and the second term is due to X-ray heating.

For SAX J1808.4–3658, many of these model parameters are well-constrained. We may adopt the distance $D = 2.5$ kpc inferred from radius-expansion X-ray bursts (in 't Zand et al. 2001). Since this is a disk-accreting pulsar, we may assume that the inner disk is truncated by the pulsar's magnetosphere at a radius $r_{\rm in}$ of order the corotation radius $r_{\rm co} = (GM_{\rm x}P_{\rm spin}^2/4\pi^2)^{1/3} \approx 30$ km (Psaltis & Chakrabarty 1999); in fact, the optical spectrum is not very sensitive to the exact value of this parameter, since the optical emission primarily arises from radii in excess
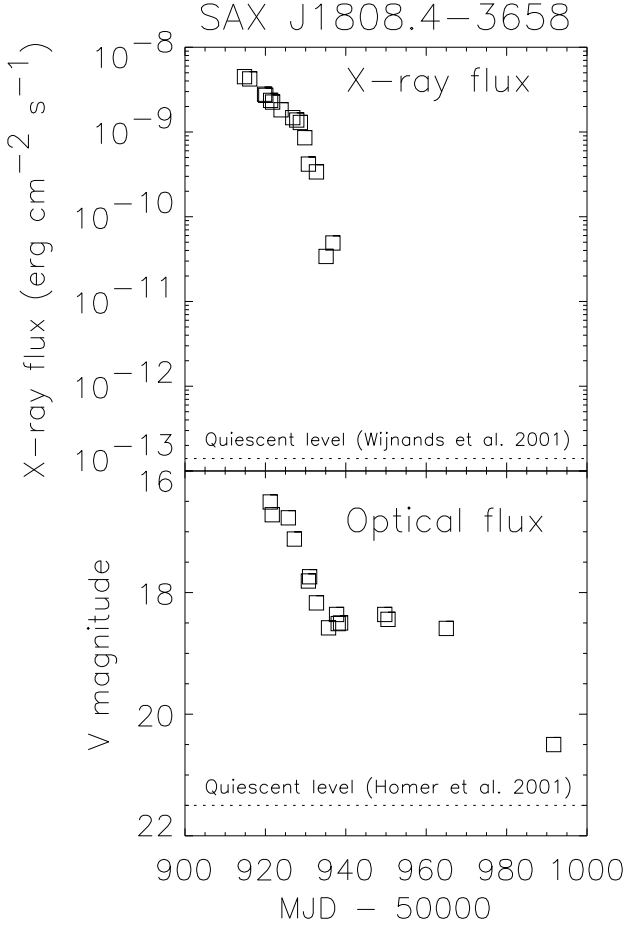
FIG. 1.— X-ray (3–150 keV) and optical flux histories during the 1998 outburst of SAX J1808.4–3658. The quiescent levels well after the outburst are also indicated. The X-ray history (taken from Gilfanov et al. 1998) contains a sharp break at MJD 50929, while the optical history shows a break at MJD 50936.
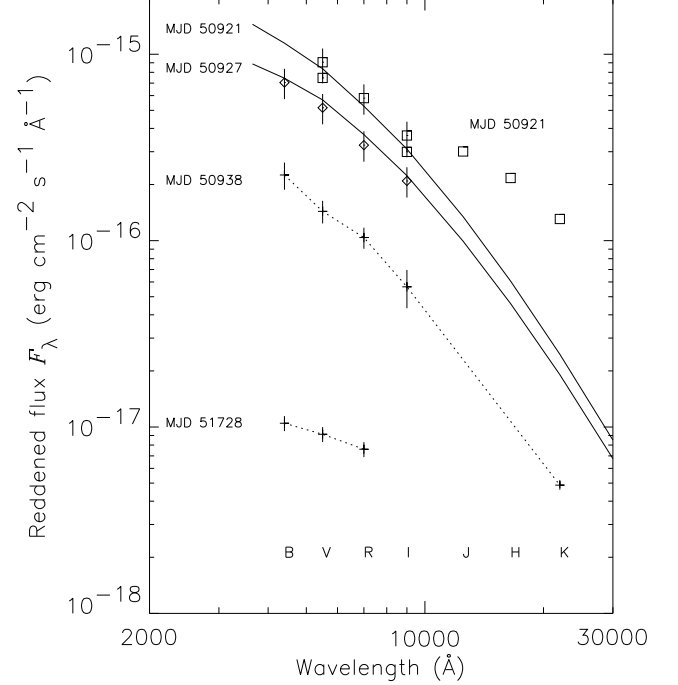

FIG. 2.— Broadband optical/IR spectra of SAX J1808.4–3658 at various epochs during the 1998 outburst. The solid curves are model fits, while the dotted curves simply indicate a rough interpolation of the data. There is a clear IR excess with respect to an accretion disk model on MJD 50921, but not on MJD 50938.

of 10^8 cm. The outer disk will be cut off sharply near the neutron star's tidal radius, $\approx R_{\mathrm{Roche}}$ (Frank et al. 1992), which will in turn depend upon the mass ratio and thus the binary inclination (Eggleton 1983). We may infer the X-ray luminosity from the X-ray flux through $L_x = 4\pi D^2 F_x$, and hence deduce the mass transfer rate $\dot{M}$. Finally, for the X-ray albedo of the disk, we use the results of previous studies of X-ray reprocessing in LMXBs which found that $\eta_d \gtrsim 0.90$, indicating that only a small fraction of the incident X-ray flux is absorbed by the accretion disk and reprocessed into the optical band (Kallman, Raymond, & Vrtilek 1991; de Jong, van Paradijs, & Augusteijn 1996).

With the model parameters set as described above, we fit the heated disk model to the observed photometry with two free parameters, $\cos i$ and the optical V-band extinction A_V. We computed our model fits on a grid with 99 values of $\cos i$ in the range 0.01–0.99 and 501 values of A_V in the range 0.00–5.00. We computed the extinction in the other bands using the interstellar reddening law of Rieke & Lebofsky (1985). For each $(A_V, \cos i)$ grid point, we fit the data for 10 different values of η_d in the range 0.90–0.99 and used only the best-fit value for that grid point. In order to ensure that we were working in the regime where X-ray heating is important (and the X-ray flux is well determined), we confined our fitting to the optical data prior to the break in the X-ray light curve at MJD 50929. The

fitting was performed simultaneously to all the *BVRI* data in Table 1 prior to that date.

Our simple disk model was able to provide a good simultaneous solution to these data. The best-fit parameters were $A_V = 0.68^{+0.37}_{-0.28}$ and $\cos i = 0.65^{+0.23}_{-0.38}$, with reduced $\chi^2 = 0.81$ (9 degrees of freedom), where the uncertainties are quoted at the 90%-confidence level. The spectral model for two epochs is shown by the solid curves in Figure 2, and a contour plot of the allowed parameter space is shown in Figure 3. The confidence levels indicated by the contours in Figure 3 are determined as described by Lampton, Margon, & Bowyer (1976). The hashed regions in Figure 3 reflect the additional lower limit of $A_V > 0.53$ set by the measured Galactic dust extinction through the Galactic disk along the line of sight (Schlegel, Finkbeiner, & Davis 1998), and the additional lower limit of $\cos i > 0.15$ set by the absence of a deep X-ray eclipse of the source (Chakrabarty & Morgan 1998). (We note that the system must lie outside the Galactic disk, given its distance and Galactic latitude.) Accounting for these additional independent limits, the best-fit parameter values are $A_V = 0.68^{+0.37}_{-0.15}$ and $\cos i = 0.65^{+0.23}_{-0.33}$. The allowed parameter space is relatively narrow in A_V with a central value only slightly larger than the Galactic value.

To investigate how sensitive our conclusions are to the adopted source distance $D = 2.5$ kpc, we refit the data for distances of 2 kpc and 3 kpc as well. For the larger distance, the confidence contours in Figure 3 were slightly displaced upward and to the right, with best-fit parameter values $A_V = 0.74^{+0.39}_{-0.34}$ and $\cos i = 0.80^{+0.14}_{-0.38}$ with reduced $\chi^2 = 0.80$. For the smaller distance, the contours were more elongated and displaced downward and to the left, with best-fit parameter values $A_V = 0.63^{+0.31}_{-0.22}$ and $\cos i = 0.39 \pm 0.35$ with reduced $\chi^2 = 0.85$.
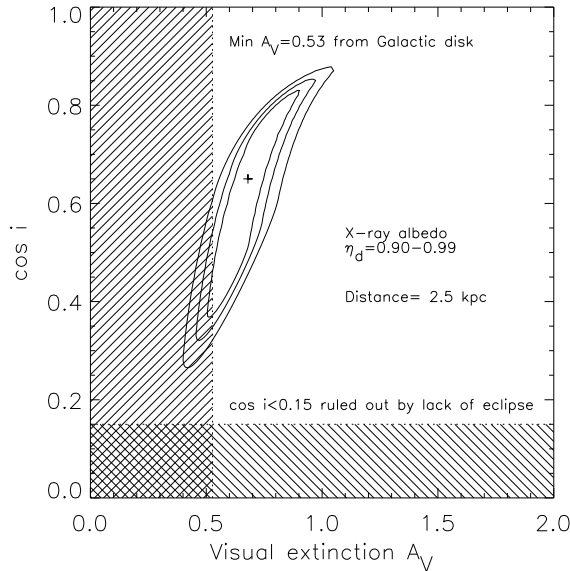
FIG. 3.— Confidence regions for $\cos i$ and A_V from spectral fitting. The best-fit ($\cos i = 0.65$, $A_V = 0.68$) is indicated by the cross, while the solid contours denote $\Delta\chi^2 = 1.0$, 2.3, 4.6 (corresponding to confidence levels of 39%, 68%, and 90%). The hashed regions indicate addition limits from the line-of-sight extinction in the Galactic disk and the lack of an X-ray eclipse.

In both cases, the fit values are quoted without accounting for the addition independent limits discussed above. The assumed distance clearly plays a significant role in determining the fit parameters, although the qualitative results of an extinction value slightly greater than Galactic and an intermediate inclination are robust.

4. DISCUSSION

We have shown that the optical spectrum of SAX J1808.4−3658 during its 1998 outburst is well fit by an X-ray–heated accretion disk model. The derived inclination range for the binary requires that the companion mass is 0.05–0.10 $M_\odot$ (Chakrabarty & Morgan 1998). This is consistent with the low companion mass deduced from the long-term average $\dot{M}$ for gravitational-radiation–driven mass transfer (Chakrabarty & Morgan 1998) and thus supports the recent prediction that the mass donor is a low-mass brown dwarf (Bildsten & Chakrabarty 2001). This inclination range is also consistent with the orbital-phase flux variability observed from the source in both the X-ray (Chakrabarty & Morgan 1998; Lee, Psaltis, & Chakrabarty 2001, in preparation) and optical (Giles et al. 1999; Homer et al. 2001) bands.

The strong infrared excess measured on MJD 50921 is clearly inconsistent with emission from the X-ray heated disk (see Figure 2). It is also orders of magnitude too bright to be due to the companion; even X-ray heating does not mitigate this, due to the small solid angle subtended by the star. On the other hand, the infrared emission on MJD 50938 is consistent with disk emission, indicating that the cause of the earlier IR excess is transient in nature. It is interesting to note that the flux density of the IR excess is comparable to the radio flux density measured from the source a week later (Gaensler, Stappers, & Getts 1999). Radio/IR emission due to synchrotron processes have been previously detected from some X-ray binaries during outburst (see, e.g., Fender 2001). The possibility of a synchrotron origin for the IR excess on MJD 50921 (as well as the radio emission) will be explored in detail elsewhere (Chakrabarty, Gaensler, & Stappers 2001, in preparation).

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